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Effects of Silica Fume and Fly Ash as Partial Replacement of Cement on Water Permeability and Strength of High Performance Concrete

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***Abstract*—Industrial byproducts such as Silica Fume (SF) and Fly Ash (FA) can be utilized to enhance the strength and water permeability characteristics of High Performance Concrete (HPC). The utilization of these industrial by products is becoming popular throughout the world because of the minimization of their potential hazardous effects on environment. This paper investigates the individual effects of Silica Fume and Fly Ash as a partial replacement of Ordinary Portland Cement (OPC) on water permeability, compressive strength, split tensile strength and flexural tensile strength of High Performance Concrete (HPC). To investigate these properties of concrete, the total investigation was categorized into two basic test groups - SF Group for Silica Fume and FA Group for Fly Ash. Seven types of mix proportions were used to cast the test specimens for both groups. The replacement levels of OPC by Silica Fume were 0%, 2.5%, 5%, 7.5%, 10%, 15% and 20% where replacement levels of OPC by Fly Ash were 0%, 5%, 10%, 15%, 20%, 25% and 30%. 1% super-plasticizer was used in all the test specimens for high performance (i.e., high workability at lower water-binder ratio) and to identify the sharp effects of Silica Fume and Fly Ash on the properties of concrete. Water-binder ratio was kept 0.42 for all cases and the specimens were tested at ages of 7, 14 and 28 days.10% Silica Fume and 20% Fly Ash showed the lowest water penetration depth of 11mm and 15 mm respectively. 7.5% Silica Fume and 10% Fly Ash were found to be optimum for maximum compressive strength, maximum split tensile strength as well as maximum flexural tensile strength.**

***Index Terms*—High Performance Concrete, Silica Fume, Fly Ash, Water Permeability, Mechanical Properties of Concrete, Replacement Levels**

I. INTRODUCTION

High Performance Concrete (HPC) is now widely used worldwide because of its high workability, high density with high modulus of elasticity, high dimensional stability with good abrasion and impact resistance, high strength and cavitations resistances. According to American Concrete Institute (ACI), High Performance Concrete is defined as, “a concrete that meets specialcombinations of performance and uniformity

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requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices". To achieve economic advantages with sustainable construction techniques, HPC has fabulous popularities.

Supplementary cementitious materials like silica fume (micro silica), fly ash, and blast furnace slag are commonly used in HPC to mobilize their pozzolanic action that improves the strength, workability, durability, resistance to cracks and permeability of HPC [1]. Silica Fume is most commonly used supplementary cementitious material which results from the electric furnace operation during the production of silicon metal and ferrosilicon alloy as an oxidized vapor. Silica Fume consists of very fine vitreous particles with a surface area between 13,000 and 30,000m^2/kg and its particles are approximately 100 times smaller than the average cement particles [2].

Permeability is defined as the coefficient representing "the rate at which water is transmitted through a saturated specimen of concrete under an externally maintained hydraulic gradient. It is inversely linked to durability. Decrease in permeability reduces deterioration of concrete caused by various factors such as chloride attack, sulfate attack, freezing and thawing, alkali-aggregate reaction, carbonation, etc. Optimum use of silica fume and fly ash must be ensured to achieve the desired strength as well as durability requirement of the structural concrete [3].

The individual contributions of silica fume and fly ash to the water permeability and strength of concrete are yet to be fully quantified. Most of the intensive research works are concentrated and focused on the compressive strength though the literature regarding research on silica fume and flyash seems to be rich. The significant technical data and research findings on tensile strength and water penetration rate are quite limited. It is therefore necessaryto investigate all the strength properties like compressive strength, split tensile strength, flexural tensile strength and water permeability characteristics of high performance concrete for different dosage (percentage as replacement of cement). Most importantly, high performance and durable concrete should have characteristics of chlorine and sulphate resistance which can be ensured by increasing the resistance to penetration of water. This type of concrete is being used in many big projects asit iseconomical as well as durable and it ensures safety. But the making of high performance concrete with sustainable durability is not an easy task because the dosage limit of admixtures (fly ash or silica fume or blending of fly ash and silica fume) play an important role and from many researches it is already proved that lower percentages of those admixtures or higher percentages cannot bring more strength or cannot make the concrete more durable. The aim of this study is to find out the 'individual effects' rather than the 'blending of fly ash and silica fume together' on water permeability and strength characteristics of high performance concrete to obtain optimum mixture percentages which can ensure durable concrete as well as economical way of ensuring sustainable development.

II. Experimental Program and Approach

A. Material of Specimen

To obtain the best percentages of mix proportions in both cases (Fly Ash and Silica Fume) separate casting of the test specimens were conducted. Blending of Silica Fume (SF) and Fly Ash (FA) were avoided as the individual effects of SF and FA were observed in this study.

Concrete materials were mixed as per standard of ASTM C 192M-07. OPC was used and its physical and mechanical properties are tabulated in Table I. Graded river sand (Sylhet Sand) passing through 1.18mm sieve with fineness modulus of 3.0 was used which were free from organic chemicals and unwanted clay. Local crushed granite aggregate passing through 12.5 mm sieve and retained on 4.75mm sieve with fineness modulus 4.01 was used which satisfy both ASTM and Indian Standard. Fresh clean water, free from chlorine, suspended solids, acids and having pH value 7.0 was used for mixing purpose.

Silica fume was supplied by Rainbow Holdings Ltd., Dhaka, Bangladesh which satisfies the requirements of ASTM C 1240. The physical andchemical analysis constituents of SF are tabulated at Table I. High Calcium fly ash was obtained from Rainbow Holdings Ltd., Dhaka, Bangladesh which satisfies the requirement of ASTM class C. The chemical proportions of fly ash are tabulated at Table I.

Super-Plasticizers (SP) can affect the concrete strength even at constant water–cement ratio [4]. The strength of both cement paste and concrete can be affected by the dosage of SP [5]. Thus, the dosage of SP was keptconstant for all the specimen mixes to identify the sharp effects of silica fume and fly ash. If the dosage of SPis varied with the silica fume and fly ash replacement percentage, thenthe variations in the concrete strength will occur not only dueto variations in the silica fume or fly ash contents but also due to change in

the dosage of SP [6]. Since the SPcontent of all the mixes was kept constant, to minimizevariations in workability,the compaction energywas variedfor obtaining proper compaction[7]. Toensure good

TABLE I. PHYSICAL AND CHEMICAL PROPERTIES OF OPC, SILICA FUME AND FLY ASH

Properties	Ordinary Portland Cement	Silica Fume	Fly Ash
Physical properties			
Specific Gravity	3.15	2.21	3.1
Initial Setting Time (Min)	115	-	-
Final Setting Time (Min)	229	-	-
Fineness as Surface Area (m^2/kg)	370	20,000	420
Chemical Properties			
Silicon Dioxide (SiO_2)	21.02%	91.4%	53.92%
Aluminium Oxide (Al_2O_3)	5.68%	1.1%	21%
Ferric Oxide (Fe_2O_3)	3.53%	0.3% - 0.5%	3.9% - 4.3%
Magnesium Oxide (MgO)	1.1%	1.3%	2.2%
Calcium Oxide (CaO)	62.25%	0.7%	4%
Sulphur Trioxide (SO_3)	3.0%	0.4%	0.6%
Sodium Oxide (Na_2O)	0.15%	0.8%	0.4% - 0.6%
Potassium Oxide (K_2O)	0.35%	0.5%	0.2%
Loss of Ignition	1.05%	2.4%	1.9%

dispersionof the silica fume at such variable dosages, highbinder content and an optimum dosage of SP were used withconstant mixing times. As the SP dosage was kept constant,while adjusting the binder content, it was considered that the mixshould not segregate athigher water–binder ratios, nor itshould be unworkable at lower water–binder ratios. The mixingprocedure and time were kept constant for all the concrete mixes investigated [7]. According to I. B.Muhit (2013), the maximum strength for concrete is obtained from a fixed dosage percentage of super-plasticizer and it is exactly 1.0% by weight of cement and the effective dosage rangesbetween 0.6% and 1.0% [8].Sikament® R2002 was used as SP because it is not only a high range water reducing admixture for promoting high early and ultimate strengths but also is non-hazardous and non-toxic under relevant safety and health issue [8]. It is a highly effective super-plasticizer with a set retarding effect for producing free flowing concrete in hot climates. It complies with ASTM C 494 Type G and B.S. 5075 Part 3[9, 10].

B. Mix Proportions of Specimen

The mixture proportions of all specimens for replacement of Silica Fume and Fly Ash are tabulated respectively at Table 2 and Table 3. The replacement levels of cement by SF were selected as 0% (control mix), 2.5%, 5%, 7.5%, 10%, 15% and 20%. And the replacement levels of percentages of cement by FA were selected as 0% (control mix), 5%, 10%, 15%, 20%, 25% and 30%. For all specimens, water/binder (w/b) ratio was kept constant and it was 0.42where the total amount ofbinder content was 480 Kg/m^3 for every specimen. Here binder refers the mixture of Cement and Silica Fume for SF study group and mixture of Cement and Fly Ash for FA study group. The mixture proportions of Binder: Fine Aggregate: Coarse Aggregate was taken as 1: 1.28: 2.2.

C. Casting of Specimen and Curing

Four types of specimens were casted to conduct all sort of test regarding strength and water permeability. Standard Sample (dimension 120mm x 200mm x 200mm) for water permeability test, Standard Cube specimen (dimension 150mm x 150mm x 150mm) for compressive strength test, Cylinder specimen (dimension 150mm diameter with 300mm height) for split tensile strength test and beam specimen (100mm x 100mm x 500mm) for flexural tensile strength test were casted. During curing period, thesamples were stored in a place free from vibration and in relatively moist air at a temperature ranges from 25ºC to 27ºC[11]. After 2 days, themold was removed and marked with symbol to identify later and finally cured under clean fresh water.

D. Testing of Specimen

To measure the workability of concrete, Slump Test [12, 13, 14, 15] and Compacting Factor Test (Derived by Road Research Laboratory U.K) were conducted. Through DIN 1048 (Part 5), thepermeability of concrete specimen was determined. The resistance of concrete against the penetration of water exerting pressure is an indication of permeability. More than 28 days and less than 35 days aged concrete were exposed either from above or below to a water pressure of 5 bars acting normal to the mold-filling direction for a period of three days. The pressure was kept constant throughout the test. Compressive strength of cube specimen as per ASTM standard was conducted by compression machine for 7, 14, and 28 days. Split tensile strength was measured by cylinder specimen and flexural tensile strength measured by beam specimen for 7, 14 and 28 days.

TABLE. II. MIX PROPORTIONS FOR SF (SILICA FUME) STUDY GROUP

Specimen ID	w/b Ratio	Cement (Kg/m^3)	Silica Fume		Aggregates (Kg/m^3)		Water (Kg/m^3)	SP (%)
			%	Kg/m^3	Fine	Coarse		
SF-I	0.42	480	0	0	616	1058	201.6	1.0
SF-II	0.42	468	2.5	12	616	1058	201.6	1.0
SF-III	0.42	456	5.0	24	616	1058	201.6	1.0
SF-IV	0.42	444	7.5	36	616	1058	201.6	1.0
SF-V	0.42	432	10	48	616	1058	201.6	1.0
SF-VI	0.42	408	15	72	616	1058	201.6	1.0
SF-VII	0.42	384	20	96	616	1058	201.6	1.0

TABLE. III. MIX PROPORTIONS FOR FA (FLY ASH) STUDY GROUP

Specimen ID	w/b Ratio	Cement (Kg/m^3)	Fly Ash		Aggregates (Kg/m^3)		Water (Kg/m^3)	SP (%)
			%	Kg/m^3	Fine	Coarse		
FA-I	0.42	480	0	0	616	1058	201.6	1.0
FA-II	0.42	456	5	24	616	1058	201.6	1.0
FA-III	0.42	432	10	48	616	1058	201.6	1.0
FA-IV	0.42	408	15	72	616	1058	201.6	1.0
FA-V	0.42	384	20	96	616	1058	201.6	1.0
FA-VI	0.42	360	25	120	616	1058	201.6	1.0
FA-VII	0.42	336	30	144	616	1058	201.6	1.0

III. RESULTS AND DISCUSSIONS

A. Effects on Water Permeability of High Performance Concrete

The water permeability (maximum penetrated water depth) of concrete for SF study group (for different replacement levels of OPC with silica fume) and for FA study group (for different replacement levels of OPC with fly ash) is represented at Fig. 1 and 2 respectively. From Fig. 1 it is very clear that very low penetration of water is allowed in SF-V type specimen where 10% OPC was replaced with silica fume. Without any silica fume, the penetration depth was 28mm and with 10% silica fume it was 11mm, which shows that, more than 60% reduction of water penetration can be achieved by mixing 10% silica fume. Silica fume contains fine size particles which fill the little spaces between the cement particles and it results denser concrete than the concrete without silica fume. Consequently, optimum dosage of silica fume decreases the permeability significantly but excessive silica fume can't.

From Fig. 2 it is evident that, very low penetration of water is allowed in FA-V type specimen where 20% OPC was replaced with fly ash. Without any fly ash the penetration depth was 28mm and with 20% fly ash it

was 15mm, that means more than 46% reduction of water penetration can be achieved by mixing 20% fly ash.

B. Effects on Compressive Strength of High Performance Concrete

For replacement of OPC by Silica Fume:

Silica fume has strong effects in compressive strength of concrete for 7, 14 and 28 days of age. The variation of compressive strength for different replacement levels of OPC by silica fume for 7, 14 and 28 days is shown in Fig.3. For 7 days concrete it was observed that maximum compressive strength (42 N/mm^2) was exhibited by SF-IV type specimen, which contains 7.5% silica fume with 92.5% OPC. The compressive strength increases almost 17% for SF-IVtype specimen compared to the control mix (SF-I) for 7 days. For 14 and 28days the maximum compressive strengths were obtained 53 N/mm^2 for SF-IV type specimen and 65 N/mm^2 for SF-IV type specimen respectively. So, it is clear that maximum compressive strength can be obtained by replacing 7.5% OPC with silica fume.

For replacement of OPC by Fly Ash:

As well as silica fume, fly ash has strong effects in compressive strength of concrete for 7, 14 and 28 days of age. The variation of compressive strength for different replacement levels of OPC by Fly Ash for 7, 14 and 28 days are shown in Fig. 4. For 7 days concrete it was observed that maximum compressive strength (49.5 N/mm^2) was exhibited by FA-IIItype specimen, which contains 10% fly ash with 90% OPC. The increase in compressive strength is 37.5% for theFA-IIItype specimen compared to the control mix (FA-I) for 7 days. For 14 and 28days the maximum compressive strengths were obtained 55.5 N/mm^2 for FA-III type specimen and 66 N/mm^2 for FA-IIItype specimen respectively. So, it can be concluded that maximum compressive strength can be obtained by replacing 10% OPCwith fly ash.

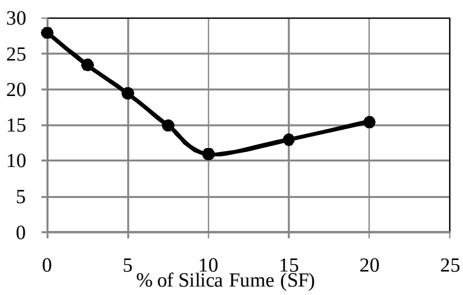

Figure 1. Water Permeability trend for Silica Fume Mixed Concrete

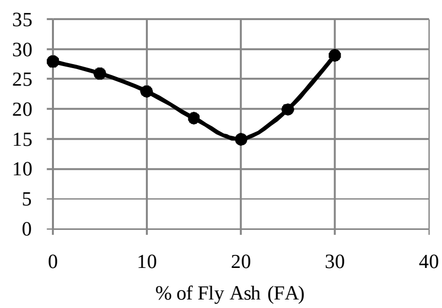

Figure 2. Water Permeability trend for Fly Ash Mixed Concrete

C.Effects on Split Tensile Strength of High Performance Concrete

For replacement of OPC by Silica Fume:

Optimum level of silica fume can play a great rolein increasing the split tensile strength. Split tensile strength for different replacement level of OPC by silica fume for 7, 14 and 28 days aged concrete are shown in Fig. 5. Maximum split tensile strength (4.0 N/mm^2) for 7 days was obtained from SF-V type specimen. For 14 days the same specimen i.e., SF-V type specimen exhibited maximum split tensile strength (4.5 N/mm^2). But for 28 days, maximum split tensile strength (5.2 N/mm^2) was obtained from SF-IV type specimen which was prepared by 7.5% silica fume replacement for OPC. So, ultimately it can be decided that the partial replacement of 7.5% OPC by silica fume was found to be optimum and 33% split tensile strength was increased from control mix (SF-I) at 28 days.

For replacement of OPC by Fly Ash:

Optimum level of fly ash can play a significant role in increasing the split tensile strength of concrete. Split tensile strength for different replacement level of OPC by fly ash for 7, 14 and 28 days aged concrete are shown in Fig. 6. Maximum split tensile strength (3.9 N/mm^2) for 7 days was obtained fromFA-III type specimen. For 14 and 28 days same case were observed that, FA-III type specimen exhibited maximum split tensile strength and for 28 days itwas 5 N/mm^2. So, ultimately it can be decided that the partial replacement of 10% OPC by fly ash was found to be optimum and more than 28% split tensile strength was increased from control mix (FA-I) at 28 days.

D. Effects on Flexural Tensile Strength of High Performance Concrete

For replacement of OPC by Silica Fume:

Silica fume has strong effects in flexural tensile strength of concrete for 7, 14 and 28 days. The variation of flexural tensile strength for different replacement levels of OPC by silica fume for 7, 14 and 28 days are shown in Fig. 7. For 7 days concrete it was observed that maximum flexural tensile strength (6.8 N/mm^2) was exhibited by SF-IV type specimen which contains 7.5% silica fume with 92.5% OPC. For 14 and 28days the maximum flexural tensile strength were obtained 8.15 N/mm^2 for SF-IV type specimen and 10.2 N/mm^2 for SF-IV type specimen respectively. So, eventually it can be decided that the partial replacement of 7.5% silica fume was found to be optimum and more than 39%flexural tensile strength was increased from control mix (0% fly ash) at 28 days.

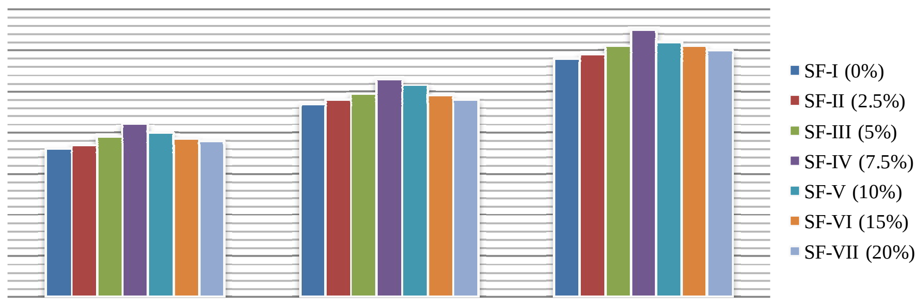

Figure 3.Compressive Strength fluctuation for different levels of Silica Fume for 7, 14 and 28 days

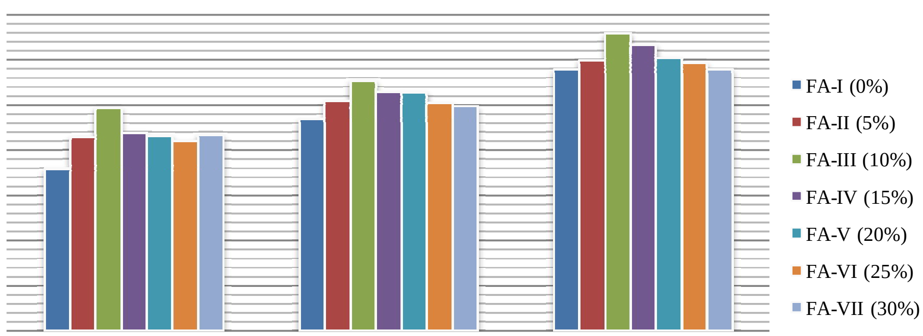

Figure 4. Compressive Strength fluctuation for different levels of Fly Ash for 7, 14 and 28 days

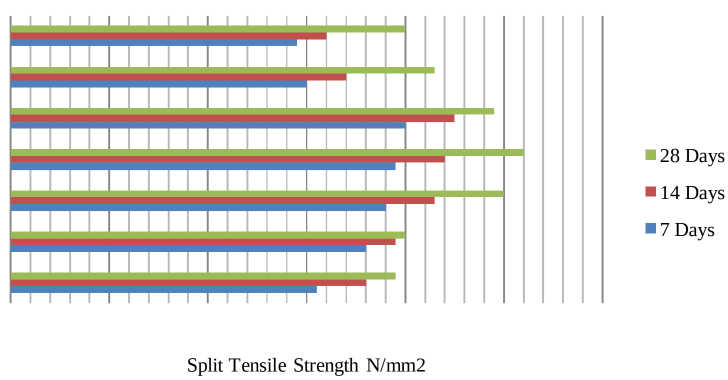

Figure 5.Split Tensile Strength fluctuation for different levels of Silica Fume for 7, 14 and 28 days

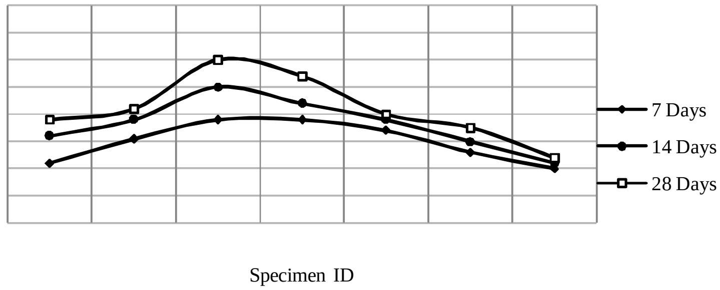

Figure 6.Split Tensile Strength fluctuation for different levels of Fly Ash for 7, 14 and 28 days

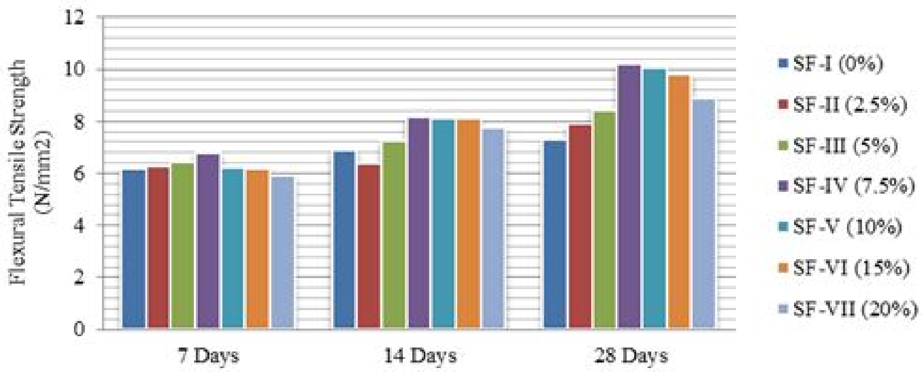

Figure 7.Flexural Tensile Strength fluctuation for different levels of Silica Fume for 7, 14 and 28 days

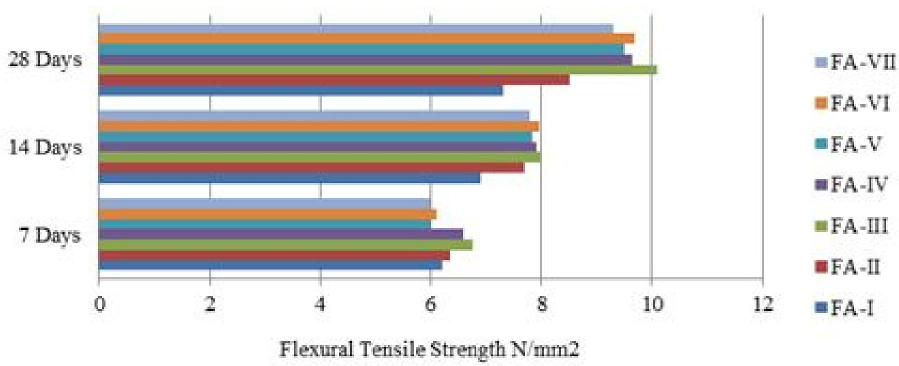

Figure 8.Flexural Tensile Strength fluctuation for different levels of Fly Ash for 7, 14 and 28 days

For replacement of OPC by Fly Ash:

Fly Ash has strong effects in flexural tensile strength of concrete for 7, 14 and 28 days. The variation of flexural tensile strength for different replacement levels of OPC by fly ash for 7, 14 and 28 days are shown in Fig. 8. For 7 days concrete it was observed that maximum flexural tensile strength (6.75 N/mm^2) was exhibited by FA-III type specimen and it contains 10% fly ash with 90% OPC. For 14 and 28days the maximum flexural tensile strength were obtained 8.0 N/mm^2 for FA-III type specimen and 10.1 N/mm^2 for FA-III type specimen respectively. So, ultimately it can be decided that the partial replacement of 10% fly ash was found to be optimum and more than 38% flexural tensile strength was increased from control mix (FA-I) at 28 days.

IV. Conclusions

From the whole investigations and research the following conclusion can be drawn:

- Pozzolanic materials have significant influence on water permeability and mechanical properties of concrete.
- 10% by weight silica fume exhibited lowest penetration of water (11mm), where lowest water permeability (15mm) for fly ash was obtained at 20% by weight.
- 65 N/mm^2 was the maximum compressive strength which was obtained for 7.5% by weight silica fume. 10% by weight fly ash showed maximum compressive strength and it was 66 N/mm^2.
- 5.2 N/mm^2 was the maximum split tensile strength which was obtained for 7.5% by weight silica fume. 10% by weight fly ash showed maximum split tensile strength and it was 5 N/mm^2.
- In case of flexural tensile strength, 7.5% by weight of silica fume and 10% by weight of fly ash proved to be optimum for maximum strength 10.2 N/mm^2 and 10.1 N/mm^2 respectively.
- The water permeability and strength characteristics of high performance concrete can be improved considerably by replacing the Ordinary Portland Cement with either silica fume or fly ash.

From literature review and from this investigation it can be recommended that blending of silica fume and fly ash is not essential to increase the water permeability and strength characteristics of concrete. Either silica fume or fly ash alone is enough to enhance the quality.

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